USAARL Report No. 2015-04

Characterization of a 4-inch Portable Shock Tube

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United States Army Aeromedical Research Laboratory

Auditory Protection and Performance Division

December 2014

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
20-01-2015	Final	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Characterization of a 4-inch Portable Shock Tube	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Jerome, Trevor W. Karch, Stephanie J. Beech, Joshua C.	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
U.S. Army Aeromedical Research Laboratory P.O. Box 620577 Fort Rucker, AL 36362	USAARL 2015-04
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
U.S. Army Medical Research and Materiel Command 504 Scott Street Fort Detrick, MD 21702	USAMRMC
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A shock tube can be used to repeatedly recreate explosive blast pressures. This report characterizes the blasts from a 4-inch diameter portable shock tube to be used in acoustic research at the U.S. Army Aeromedical Research Laboratory. The data from initial testing show that the shock tube has a dynamic range spanning 130 to 170 dB sound pressure level (SPL), and A-durations that usually fall between 0.5 and 2 milliseconds. These ranges qualify the shock tube as an appropriate apparatus for evaluating hearing protection devices using American National Standards Institute S12.42-2010.

15. SUBJECT TERMS

Shock tube, impulse, noise, shock wave, acoustic test fixture

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Loraine St. Onge, PhD
					19b. TELEPHONE NUMBER *(Include area code)*
UNCLAS	UNCLAS	UNCLAS	SAR	20	334-255-6906

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Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgements

The authors wish to express their sincere gratitude to the following persons for their significant contributions:

- LTC D. Scott McIlwain for his oversight as Division Chief;
- Dr. William Ahroon, Ph.D. for his oversight as PI; and
- Mr. Robert Williams for his oversight as AI and ORISE mentor.

This research was supported in part by an appointment to the Postdoctoral and Postgraduate Research Participation Program at the U.S. Army Aeromedical Research Laboratory administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the U.S. Army Medical Research and Materiel Command.

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Introduction

Tinnitus and hearing loss have been reported as the two most prevalent service-connected disabilities for veterans receiving compensation since fiscal year (FY) 2005. The 2013 Department of Veterans Affairs (VA) Annual Benefits Report states there were over 1.8 million auditory disabilities for which veterans were receiving compensation at the end of FY 2012. In the same report, an increase of 12.2 percent was noted from FY 2011 in the number of veterans receiving compensation for service-connected auditory acuity impairment disabilities (Department of Veterans Affairs, 2013).

Exposure to blasts such as those generated by improvised explosive devices (IEDs), rocket-propelled grenades (RPGs), and/or land mines are known to cause both tinnitus and hearing loss (Sayer, 2008). Intensity levels exceeding 120 decibels (dB) sound pressure level (SPL) can cause permanent auditory damage, depending on the characteristics of the sound (Spoendlin and Brun, 1973). The extent of ear damage and/or hearing injury resulting from exposure to blast pressure waves is determined by three characteristics of the blast: rise time, duration of positive phase (A-duration), and peak pressure (Kerr and Byrne, 1975). Shock tubes can produce blasts in a controlled environment, which contain elements that are acoustically similar to those produced by military explosives. The dynamic range of the shock tube determines the types of experiments to run.

An acoustic wave travels as molecules in the air displace each other, initiated by a moving medium. Under most conditions, there is a slight increase in atmospheric pressure and an insignificant change in temperature. Blast waves are formed by a shock tube facilitating the very rapid expansion of air, forming a travelling front. The difference in pressure resulting from blast compared to the atmospheric or other environmental pressure of the medium before the blast is the blast overpressure (Mayorga, 1997). The molecules in the air are accelerated at the blast front, and there is a significant increase in temperature, resulting in the acoustic wave travelling faster than the speed of sound.

Waveforms recorded by each transducer show that the shock waves of higher amplitude resemble the Friedlander waveform. The Friedlander waveform, shown in figure 1(Mediavilla Vara, et al., 2011), is composed of a sharp peak of positive pressure, a more gradual descent to negative pressure (relative to atmospheric pressure), and then a recovery of pressure back to equilibrium (Baker, 1973; Friedlander, 1946).

The American National Standards Institute (ANSI) is responsible for the oversight of standards development and accreditation in the United States. ANSI standard S12.42-2010 specifies testing for impulsive noise measurements and hearing protection devices (HPDs) using acoustic test fixtures (ATFs). The standard specifies three regions of free-field peak sound pressure levels to be tested: 166 to 170 dB, 148 to 152 dB, and 130 to 134 dB, with each blast having an A-duration between 0.5 and 2 milliseconds (ms). Before the acquisition of the portable 4-inch (in.) shock tube, the smallest shock tube in use at the U.S. Army Aeromedical Research Laboratory (USAARL) reliably produced blasts in the higher two intensity regions, but not in the

lower region. This report demonstrates the wide range of free-field peak SPLs attainable with the portable 4-in. shock tube, including levels in all three regions specified in ANSI S12.42-2010.

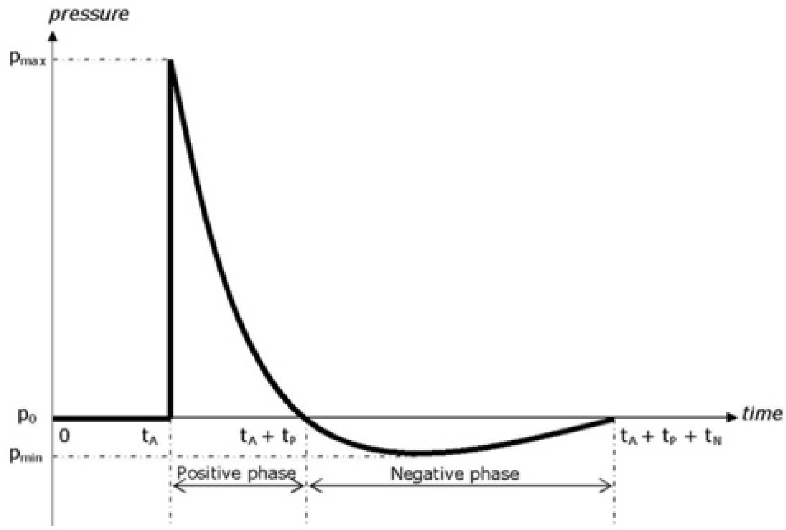

Figure 1. Classic Friedlander shock wave.

Methods

A 4-in. diameter portable acoustic shock tube was used to conduct impulsive noise testing. The acoustic shock tube was designed as a copy of a similar apparatus housed in the Taft Laboratories of the National Institute for Occupational Safety and Health (NIOSH) in Cincinnati, Ohio, with the exception of the pneumatic trigger being replaced by a manual spring-loaded trigger in the USAARL model. The shock tube was loaded with either one or two sheets of Mylar® film, and the compression chamber was filled with compressed air. The Mylar® film provided a membrane that was burst either automatically, due to the force of the compression chamber pressure exceeding membrane tensile strength, or manually, with a spring-loaded needle. The thickness of the Mylar® film and the pressure in the compression chamber of the shock tube varied throughout the study.

A total of 126 shots were fired and analyzed using compression chamber pressures ranging from 5 to 110 pounds per square inch (PSI), incrementing at approximately 5 PSI. Six microphone transducers were used to capture the data. The microphones used in the current study included one of each: Brüel and Kjær 1/8-inch condenser microphone, Brüel and Kjær 1/4-inch condenser microphone, GRAS Sound and Vibration 1/4-inch condenser microphone, GRAS Sound and Vibration pencil microphone, PCB® pencil microphone, and a PCB® 1/4-inch probe transducer. Each transducer was powered by one of two NEXUS™ amplifiers, routed from a National Instruments Data Acquisition (DAQ) device, which was bussed to a laptop computer running MATLAB®. One second of data per channel, starting one-tenth of a second before the blast peak, was recorded at a rate of 500,000 samples per second. These recordings were post-processed in MATLAB® to find the A-duration and peak level of each shot, as reported by each

microphone. Shock wave peaks were exponentially fit to each waveform in MATLAB®, since the different types of transducers do not perform equally for impulse noise at the levels required for this study.

Results

Blast waves were created according to the test protocol. Several attempts were made to create a blast in which the Mylar® film would rupture before reaching a target pressure, since the maximum pressure attainable for each test parameter (i.e., thickness and number of sheets used) was unknown prior to testing. Conversely, additional attempts to create a blast wave were required for configurations wherein the Mylar® film was manually punctured, but the sheet did not tear and a shock wave was not produced. Insufficient pressure within the compression chamber possibly led to the Mylar® film requiring to be manually punctured in the absence of a blast wave. In this scenario, a single puncture hole was created in the Mylar® film, and pressurized air would seep out of the chamber. The data from these failed manual triggers were discarded. The 126 shots that produced an audible "pop," indicating the generation of a shockwave, were saved for post-data collection processing and analysis.

Peak pressures for each of the Mylar® film configurations separately can be seen in figures 2 through 12, at each of tested compression chamber pressures. Each figure shows a configuration with one or two sheets of Mylar® film having thickness of 1-, 2-, 5-, or 10-mils, using either the (s) type, which was found to rupture at lower pressures, or the (a) type, which hereafter is the type used when no type is indicated. Microsoft® Excel® was chosen to create the graphs and trend lines for its graphical ease. Trend lines were chosen based on either a linear, logarithmic, or polynomial fit, whichever was deemed best-fitting based upon visual inspection of its layout over the corresponding data. A logarithmic fit would be best suited for ideal conditions with no non-linear effects and experimental oddities, but the given trend lines were chosen for the purpose of predicting shock-wave peak pressure for future studies with this shock tube. Data from each configuration are shown together in figure 13, to act as a quick reference in future work. The A-duration of recordings per test paradigm can be seen in figures 14 and 15.

Figure 2 shows the measured peak-pressure collected from the shock tube blasts with one sheet of Mylar® 10-mils thick. This configuration allowed for a broader range of pressures in the compression chamber than other configurations. The difference in pressure range is due to a procedural advantage of the thickness of the 10-mil Mylar® film. For pressures under 105 PSI, the chamber was pressurized to at least 105 PSI before being lowered to the blast pressure. This process of exceeding the desired pressure in the compression chamber causes the diaphragm to deform to a convex partial sphere. For most configurations, this deformation at least partially returns back to the original shape. However, the 10-mil Mylar® film held its shape even after decompression to the desired detonation pressure allowing greater range of blasting pressures. A change is noted in resultant blast wave peak pressure in these data between 95 and 100 PSI. An explanation for this behavior could not be found. A linear curve was fit to the data series for this configuration, highlighting the constant shock wave pressure for varying compression chamber pressure using this configuration.

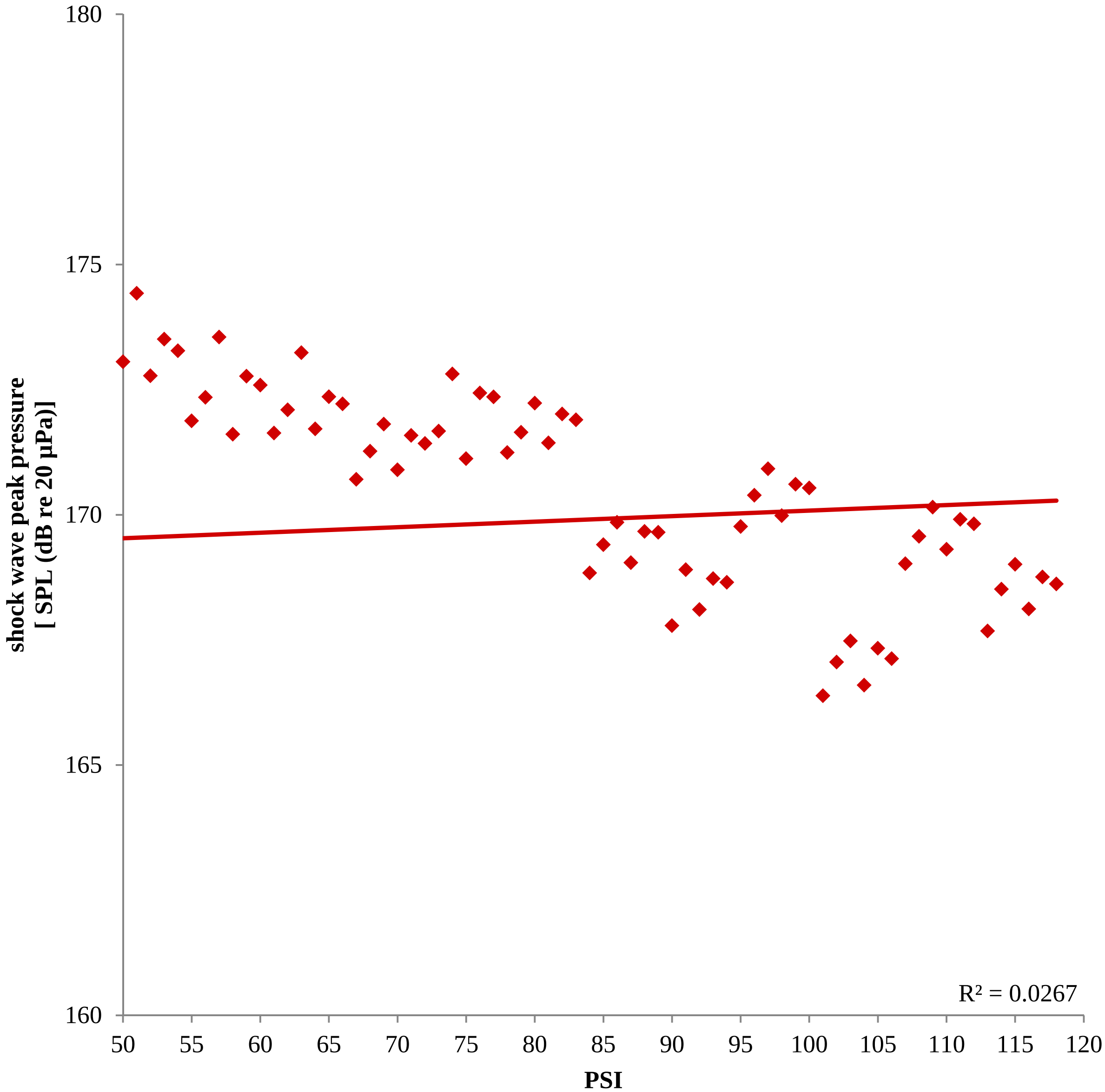

Figure 2. 10-mils, one sheet, linear fit.

Figure 3 displays the shock tube blast data points when two 5-mils Mylar® sheets were used, while figure 4 shows the same Mylar® film type but with one sheet per blast. A linear fit was used for the two-sheet data points, since the results did not seem to fit any particular pattern. In addition to different Mylar® film stresses and other elastic property effects arising from sealing two sheets together, the non-linearity in the data is suspected to arise from differences in the rate of air flow between the two sheets and the amount of time between the first and second sheet failure. A third-order polynomial fit was used for the single-sheet paradigm due to the configuration of the recorded data points.

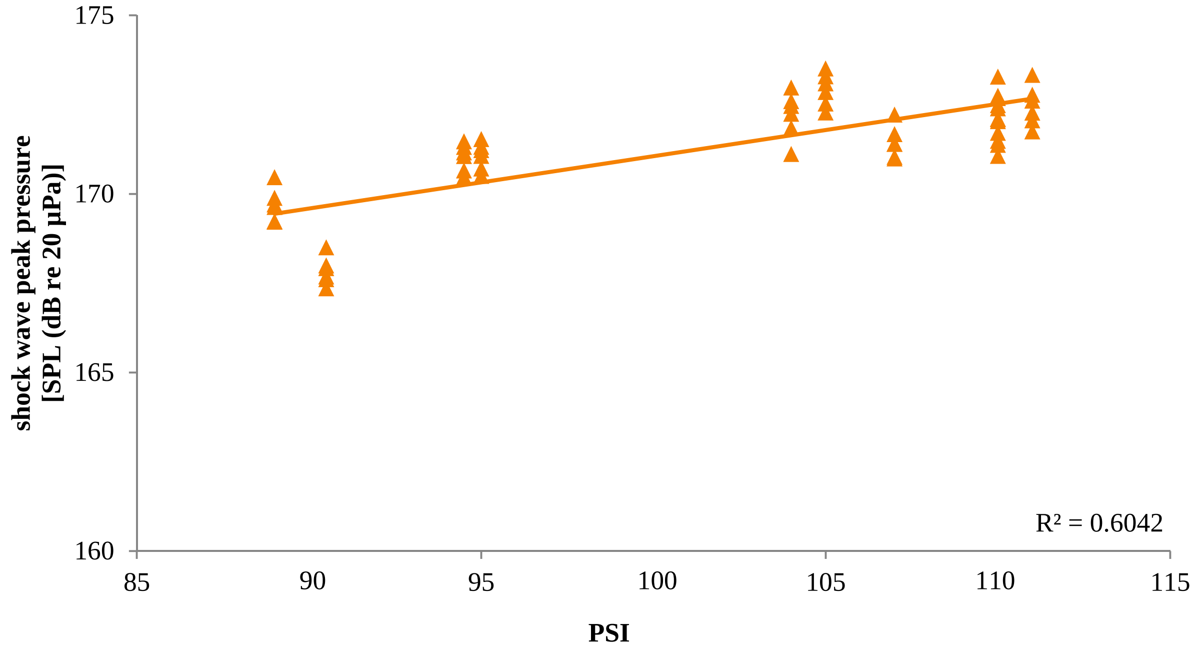

Figure 3. 5-mils, two sheets, linear fit.

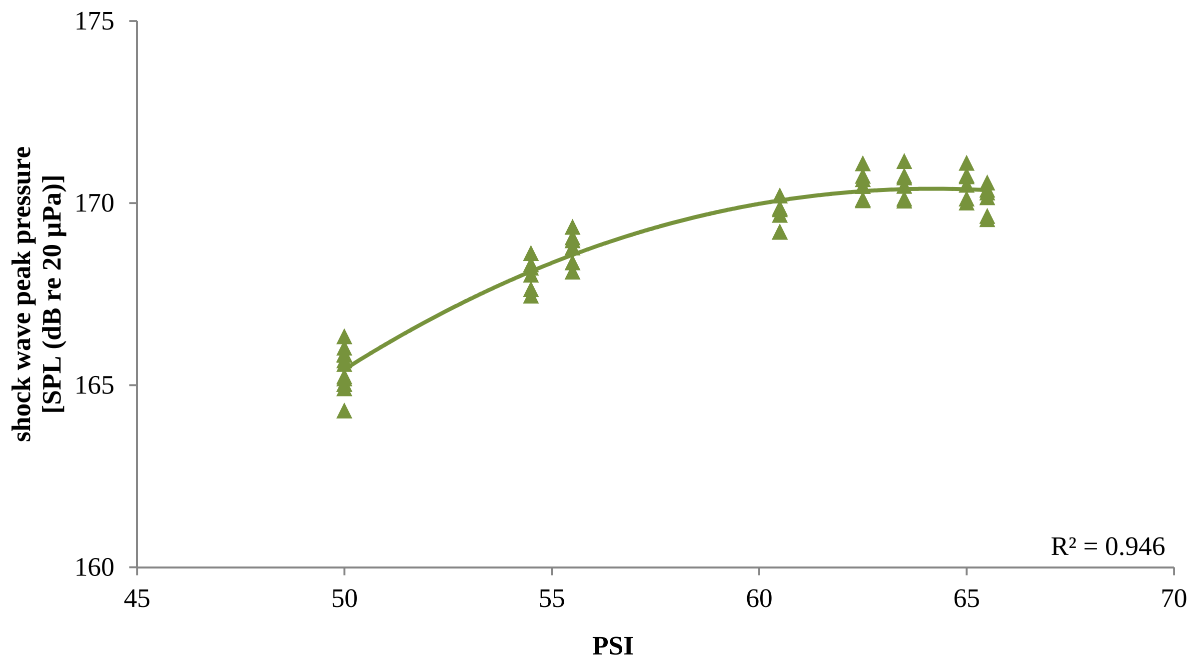

Figure 4. 5-mils, one sheet, third-order polynomial fit.

Figures 5 through 8 displays the data points of recorded blasts with use of 2-mils thick Mylar® film, and figures 9 through 12 display the data for blasts produced with 1-mil thick film. Figure 5 shows a fourth-order polynomial fit for two sheets of 2-mils (a) thick Mylar® film, while figure 6

shows one sheet of 2-mils (a) Mylar® film using a third-order polynomial fit. Figure 5 indicates the fit presented with the data in all configurations match better near the maximum limit of each configuration's maximum pressure. Figures 7 and 8 mirror figures 5 and 6 with regard to the total number of sheets of Mylar® film used. However, the Mylar® type used in the creation of the blast waves were type (s) rather than type (a). Additionally, a fifth-order polynomial was used to fit the data from two sheets of Mylar® and a logarithmic fit was used to fit the data from one sheet.

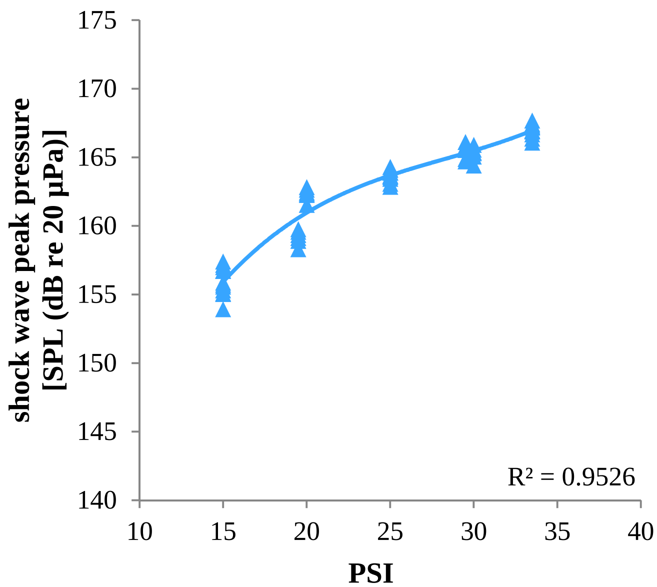

Figure 5. 2-mils (a), two sheets, fourth-order polynomial fit.

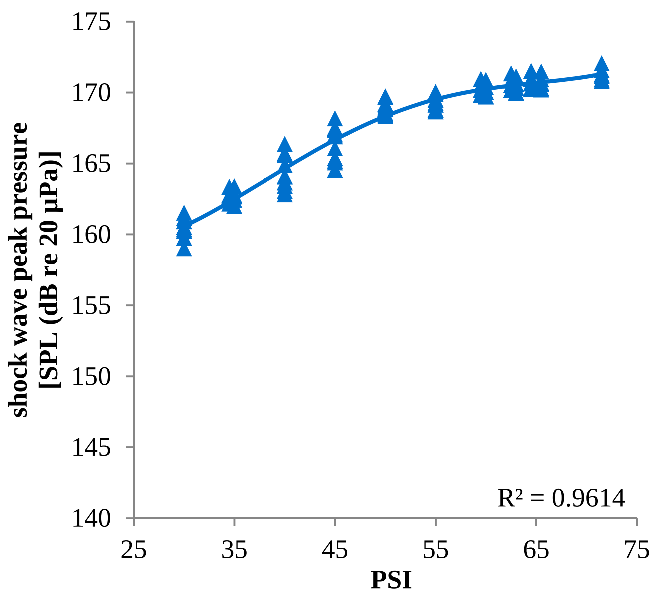

Figure 6. 2-mils (a), one sheet,third-order polynomial fit.

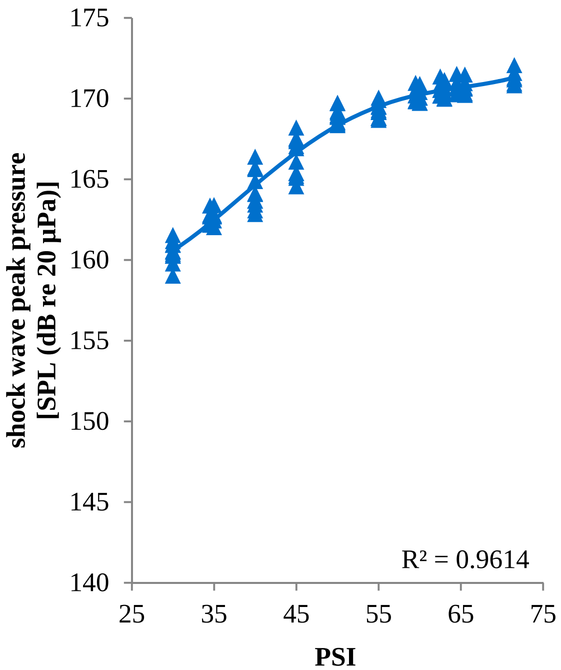

Figure 7. 2-mils (a), one sheet, third-order polynomial fit.

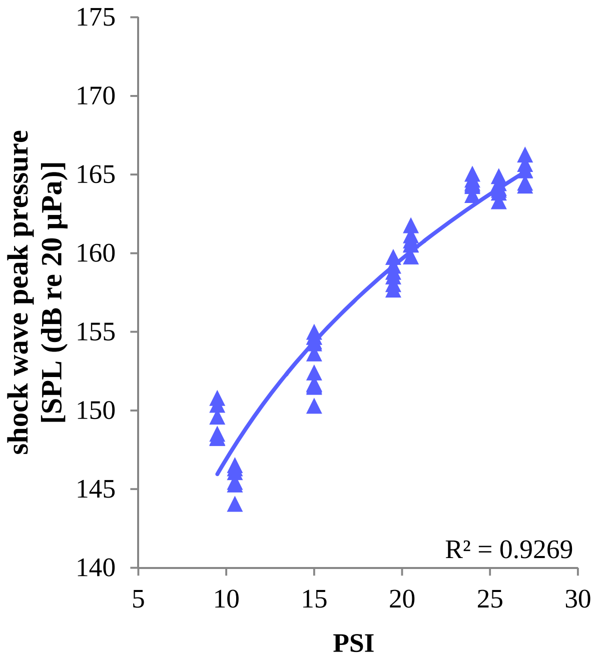

Figure 8. 2-mils (s), one sheet, logarithmic fit.

Figures 9, 10, 11, and 12 reflect identical test parameters as figures 5, 6, 7, and 8, respectively. However, a 1-mil Mylar® film sheet(s) was used rather than the previously reported 2-mils Mylar® sheet(s). Polynomial fits were used for these last figures 5 through 8, with third-order polynomial fits for Mylar® type (a) and second-order polynomial fits for type (s). Outliers in the recorded data in figures 10 and 11 were noted at the lower range (5 and 10 PSI, respectively) of tested compression chamber pressure levels.

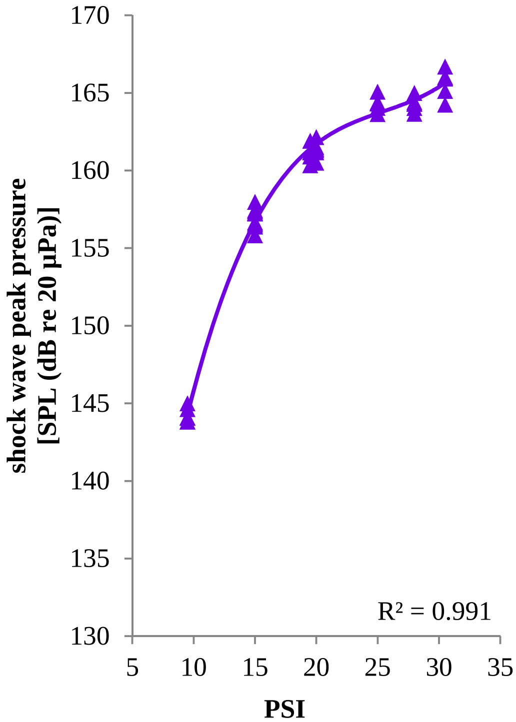

Figure 9. 1-mil (a), two sheets, third-order polynomial fit.

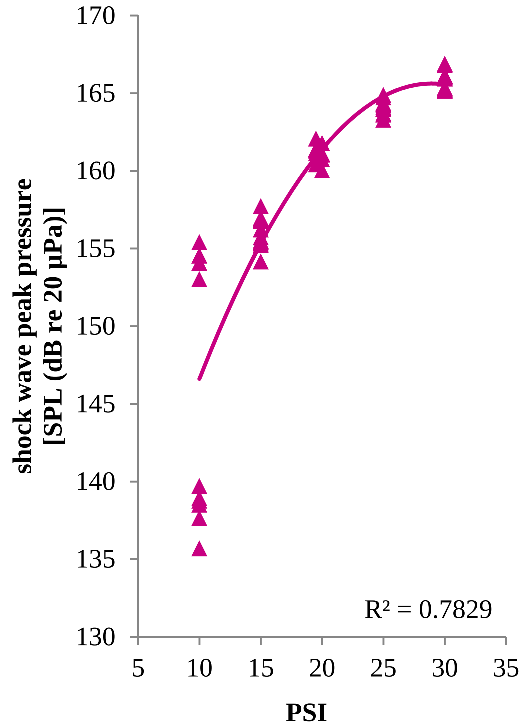

Figure 11. 1-mil (s), two sheets, second-order polynomial fit.

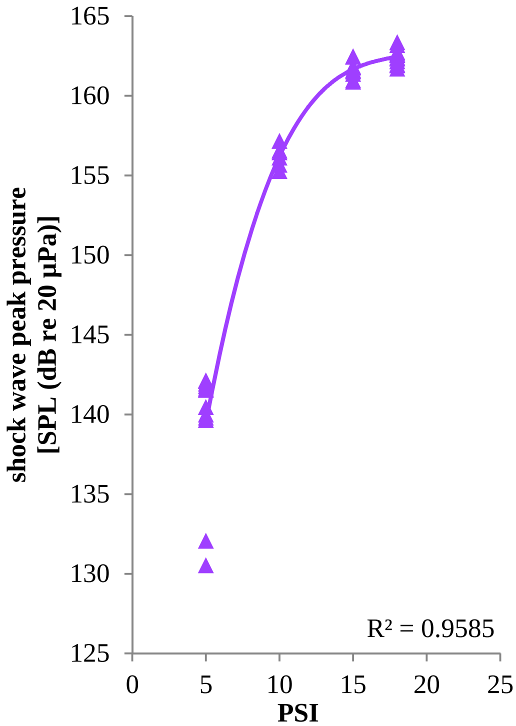

Figure 10. 1-mil (a), one sheet, third-order polynomial fit.

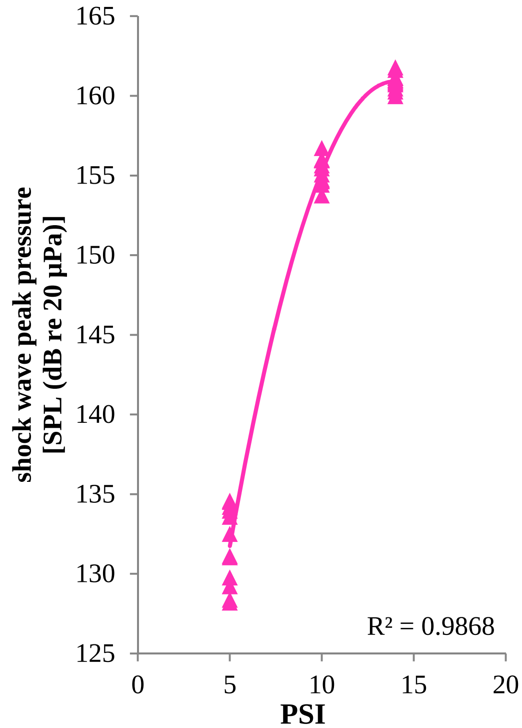

Figure 12. 1-mil (s), one sheet, second-order polynomial fit.

The peak pressure data for all recorded shots can be seen in figure 13. This summarizing graph includes the previously reported trend lines observed in figures 2 through 12. Fitting curves overlap over the entire useful range of compression chamber pressure using one or more configurations. Shock wave pressures above 140 dB would be difficult to reproduce below a compression chamber pressure of 5 PSI with any Mylar® film configuration. The shock tube used in the current test protocol was not able to exceed compression chamber pressures of 111 PSI. This limitation of the shock tube maximum compression chamber pressure is convenient, as the shock tube's standard operating procedures specify 120 PSI as the limit for safe use. In addition to using the full range of the shock tube's useful compression chamber pressure, the generated blasts covered a span from well below 130 dB to over 170 dB SPL.

When testing HPDs on ATFs, specific ranges of acceptable A-durations for the shock wave blasts exist. ANSI S12.42-2010 notes that the A-duration must be greater than or equal to 0.5 ms, with the maximum permissible A-duration of 2 ms. Figure 14 provides a histogram of the A-durations of the shock wave blasts generated during this study. Six transducers recorded each of the 126 shock tube blasts. Out of the 756 recordings made with the various configurations, 97.2 percent had an acceptable A-duration for ATF testing.

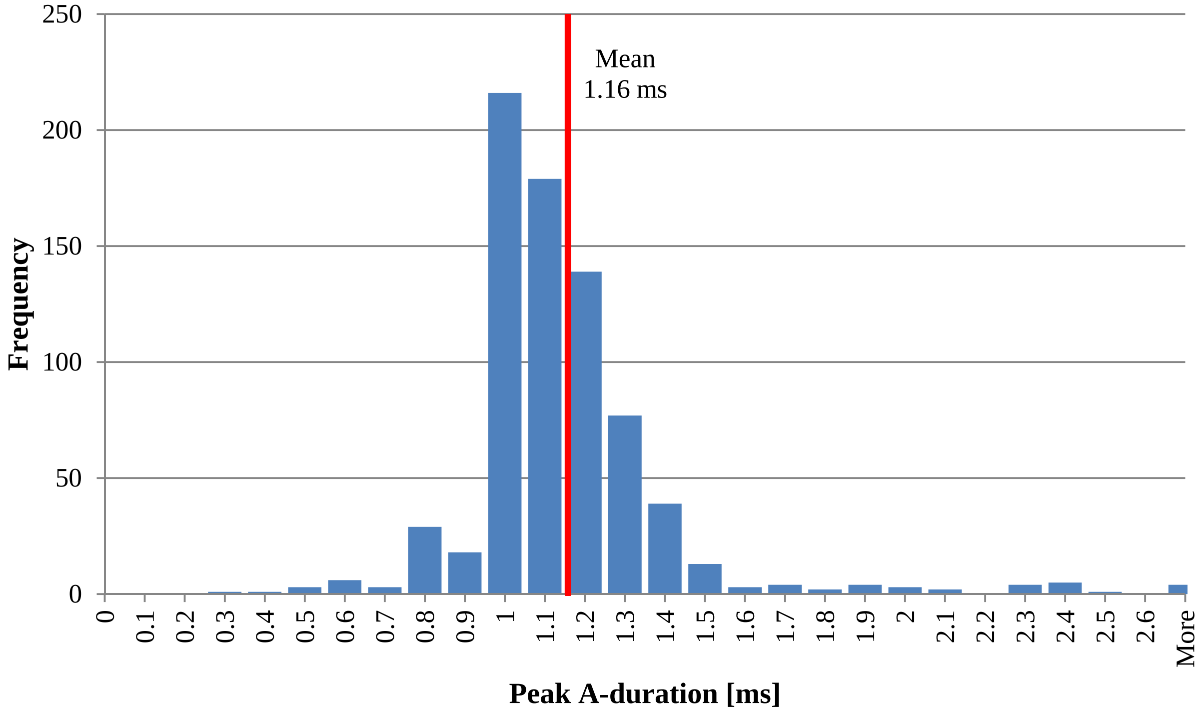

Figure 14. Histogram of shock wave peak A-duration for all 756 recordings of the 126 blasts.

Figure 15 shows the vast majority of A-duration measurements fall within the limits specified 0.5 to 2 ms range. Three configurations yielded A-duration times that were too short, making a total of five recordings. The configuration with two sheets of 2-mils (s) Mylar® film had one recording with 0.308 ms. When analyzing the A-durations of the recordings obtained with the 1-mil (s) in either the one or two sheet condition, each had two recordings that were under 0.5 ms. Blasts with a duration of 0.287 and 0.404 ms was recorded when two sheets were used, while a duration of 0.489 and 0.495 ms was recorded when one sheet was used.

Four configurations yielded A-durations that were above the 2 ms threshold. There was one recording with an A-duration of 7.233 ms recorded using two sheets of 2-mils (s) Mylar® film, and a recording of 39.168 ms recorded using one sheet of 1-mil (a) Mylar®. Since those are single measurements that were part of blast recording with five other transducers which all reported A-durations of less than 2-ms, these two outlying A-durations are most likely incorrect. Note that those two outliers were measured using the PCB® 1/4-inch probe. The two other configurations that yielded four and ten A-durations exceeding 2 ms were the two sheets of 1-mil (a) Mylar® and one sheet of 1-mil (a) Mylar®, respectively. The standard-exceeding values for the former ranged from 2.311 and 2.469 ms, and for the latter from 2.012 to 4.464 ms.

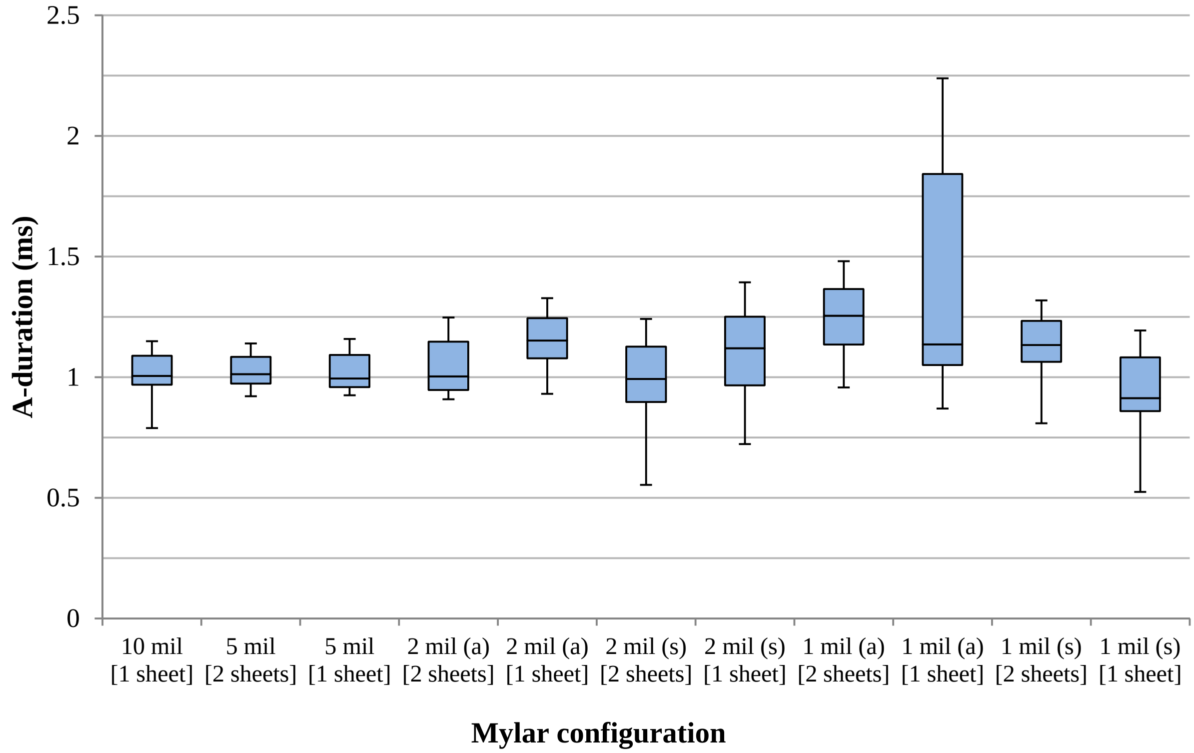

Figure 15. Shock tube impulse A-durations for various Mylar® configurations.

Discussion

The values reported in this study may be used to plan testing for ATF evaluation of HPDs or other uses pertinent to the Laboratory. The values given should be used as approximate guidelines for producing the desired pressures, but the actual impulse characteristics should be obtained using established processing techniques, as variations may arise between what is reported here and actual results due to ambient temperature, relative humidity, room reflection characteristics, Mylar® film irregularities, or other reasons. Note that the peak pressure value is only the maximum pressure of the original shock front. Higher pressures may be observable when the blast wave interacts with reflections of itself in regions known as Mach stems, or in other nonlinear interference. These pressures can exceed the peak pressure of the original shock front by several orders.

ANSI S12.42-2010 specifies testing methods using impulsive noise. ANSI S12.42-2010 section 10.1 notes that three specific ranges of peak pressures (dB SPL) are to be used while testing with ATFs, which are from 130 to 134 dB, 148 to 152 dB, and 166 to 170 dB. Using the configuration of one sheet of 1-mil (s) Mylar® film and a compression chamber pressure of 5 PSI, several readings recorded peak pressures within the first range, 130 to 134 dB. While this is the only configuration yielding most results within this peak range, other sizes of Mylar® film exist that were not tested during this evaluation, including a 0.5-mil size. Further investigation could show that configurations of Mylar® film sizes less than 1-mil in thickness may be better suited to produce shock waves at peak pressures in this first range and using higher compression

chamber pressures. The second range of 148 to 152 dB was best reproduced with one sheet of 2-mils (s) compressed at 10 PSI, but configurations of any smaller size Mylar® may be able to perform at the target range if the compression chamber pressures are optimized for such testing using those setups. Lastly, the range from 166 to 170 dB was achieved with all of the configurations using Mylar® film sizes of 2-, 5-, and 10-mils, using compression pressures ranging between 25 and 110 PSI.

Conclusions

The presented data show patterns of 11 specific Mylar® film configurations using the portable 4-in. shock tube, varying in number of sheets from one to two, and varying in thickness from 1- to 10-mils. The current protocol found that the USAARL 4-in. portable shock tube is capable of producing repeatable shock tube blasts from 130 to 170 dB (SPL re 20 µPa). This dynamic range is useful when testing HPDs on ATFs using established standards such as ANSI S12.42-2010. Further, it was found that 97 percent of the blasts from this study had qualifying A-durations for ATF tests as specified in ANSI S12.42-2010.

Recommendations

Future testing is recommended to include Mylar® film sheets of thickness less than 1-mil, and combinations with one, two, or three sheets of all sizes that would likely produce peak pressures within the designated testing ranges specified by ANSI S12.24-2010. Discrepancies at the lower pressure limits for some of the configurations remain unexplained until further investigation can be done.

Studies involving ATFs should use the findings in this report as guidelines for testing with target shock wave peak pressures and A-durations. Actual data should be measured and checked to ensure that they fall within the desired criteria.

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